



Adding a diversity of legumes to a crop decision-support system: Maintaining satisfactory accuracy while keeping the model simple

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ABSTRACT

In a context of economic and environmental concerns in agriculture, legumes appear to be suitable alternative crops to diversify current cropping systems and reduce their dependence on synthetic nitrogen (N) fertiliser and protein from imported soya bean. However, legume-based cropping systems may increase N losses through nitrate leaching if the N available from legumes does not coincide with subsequent crop requirements. To help agricultural advisers manage N in these systems, we adapted the decision-support system Syst'N®, designed to assess N losses in cropping systems, to simulate three annual and one perennial legume crops: pea, faba bean, soya bean and lucerne. To this end, we adapted and simplified existing submodels of legume functioning to include them in Syst'N, to keep the latter simple. We adapted the submodels "BNF" (i.e. biological N fixation) from the STICS model and "dormancy" from the CropSyst model. We also added the ability to enter the flowering date to improve predictions (improvement in N fixation's rRMSE from 57% to 41% and EF from 0.57 to 0.77). The equations and associated parameter set developed for the four legume crops yielded satisfying predictions of crop biomass (rMBE = 9%, EF = 0.82, rRMSE = 39%) and N content (rMBE = 5%, EF = 0.76, rRMSE = 37%). These performances support the philosophy of Syst'N® that requires minimising the number of additional parameters for users when representing new crops or processes.

1. Introduction

The agricultural revolution after 1945 led to a major intensification of French agriculture due to the increasingly intensive use of mechanisation and chemically synthesised inputs, which was enabled by technical progress. This intensification and the organisation of agriculture into sectors have fostered specialisation of production systems with a geographical separation between crop and livestock production and increasingly shorter cropping sequences (Ferrant, 2009). These changes, based on choosing crop species that maximise profit in the short term,

led to the abandonment of species that provided recognised agronomic and ecosystem services such as legumes (Schott et al., 2010). Moreover, historical choices of public policies (e.g. subsidies for cereal production), research and engineering triggered the marginalisation of legumes (Magrini et al., 2016). Since the 1990 s, however, growing awareness of negative externalities associated with cereal-based intensive systems (e.g. environmental pollution, greenhouse gas emissions, loss of biodiversity) has prompted some stakeholders in the agricultural sector to seek more economical and environmentally friendly practices (Voisin et al., 2013). In this context, legumes appear to be good alternative crops to

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diversify current cropping systems and reduce their dependence on synthetic N fertiliser and protein from imported soya bean (Carof et al., 2019). Comparing N fixed by legumes vs. industrial sources, Crews and Peoples (2004) showed that developing legume-based cropping systems could lead to more sustainable agriculture. Indeed, legumes have the unique ability to fix N from the air (N_2), thus reducing their need for N fertilisation; in Europe, legume crops are usually not fertilised (Cernay et al., 2017). Biological N fixation (BNF) by grain/forage legumes also benefits subsequent crops by leaving more N in the soil than cereals do (Herridge et al., 1995) and through mineralisation of N-rich plant residues incorporated into the soil after crop harvest, thus increasing soil N fertility (Justes et al., 2001). However, legume-based cropping systems may increase N losses through nitrate leaching if the N available from legumes does not coincide with subsequent crop N requirements (Muller et al., 1993; Cellier et al., 2015; Plaza-Bonilla et al., 2015; Voisin et al., 2015). Legumes differ in their N-fixation efficiency, which depends on the response of their BNF to abiotic factors (e.g. soil mineral N content, temperature, soil water content) and their physiological functioning (Guinet et al., 2018). Therefore, legume BNF and N pre-crop effects must be quantified over time to improve the design of sustainable cropping systems that include legumes. Doing so requires improving quantification of benefits for subsequent crops from legume BNF and its influence on N losses, and thus environmental pollution (Liu et al., 2011).

In this context, agricultural stakeholders need to design new cropping systems using decision-making tools that consider legumes and that can estimate their environmental impacts. Since the 1960s, many crop models have been developed to address a variety of objectives, but only a few are directly used by practitioners to simulate N dynamics in legume-based cropping systems. This arises from a lack of user-friendly interfaces, low availability of input parameters and failure to consider users' constraints and knowledge (Prost et al., 2012). Meanwhile, users in the environmental field and agricultural advisers use indicators or simple tools that fail to simulate N-loss dynamics and to understand weaknesses of cropping systems.

As an operational tool for quantifying N losses at the multi-year scale of a cropping system, Syst'N® (Parnaudeau et al., 2012) predicts N dynamics under the most common crops in France. Syst'N is used mainly by agricultural advisers for regions with strong environmental issues (especially nitrate emissions); thus, it must estimate N losses and help discuss and design more sustainable cropping systems. Stakeholders involved in water and agricultural management who use Syst'N need it to be applicable to a variety of cropping systems that include less common crops, especially legumes (as grain or forage). In the first version of Syst'N (2013), pea (*Pisum sativum* L.) was the only legume crop parameterised. Consequently, there was a real need to extend the scope of Syst'N for users and adapt it to new cropping systems with a wider variety of legume crops.

Accordingly, this study developed, evaluated and validated Syst'N predictions for several common legume species: faba bean (*Vicia faba* L.), soya bean (*Glycine max* L.) and lucerne (*Medicago sativa* L.). Pea was parametrised again for the new equations added to predict the other legume species considered, and predictions for pea were also evaluated. This adaptation of the model is crucial because satisfactory simulation of growth and N uptake is essential to meet Syst'N's ultimate goal, which is to estimate N emissions to the environment.

We adapted Syst'N by choosing and adapting generic equations that could simulate N dynamics for several legumes without decreasing its user-friendly aspect. The design criteria for adapting Syst'N to four legumes included: (i) the ability to simulate growth and N uptake of annual and perennial legumes, (ii) the ability to simulate soil N dynamics and content during and after a crop cycle sufficiently well (e.g. residual N effects of legumes), (iii) avoiding the need for users to provide additional input data, (iv) limiting the number of additional parameters needed for new crops and (v) adapting equations from updated knowledge and models. We assumed that adapting Syst'N to a wide range of legumes would meet these criteria.

2. Materials and methods

2.1. The crop model Syst'N

Syst'N is a model-based decision-support system (DSS) developed to estimate N losses in cropping systems and promote better N management in rural areas. The French National Research Institute for Agriculture, Food and Environment (INRAE) and eight French agricultural institutes developed Syst'N together. The objective was to meet the needs of stakeholders involved in water and agricultural management for an operational tool that could predict N losses at the multi-year scale of cropping systems. Since 2005, Syst'N has been co-designed with end-users to adapt it further to their needs (Cerf et al., 2012), in an iterative process with agricultural advisers, research and development institutes, applied research institutes and environmental agencies.

The Syst'N version described by Dupas et al. (2015) added a soil-crop model to simulate soil N transformations, crop growth, N uptake, water balance and N losses towards water (e.g. nitrate) and air (e.g. ammonia, N_2 and nitrous oxide) on a daily time step. The input data required include the crop sequence, agricultural management practices, soil and climate. The equations in the biophysical model combine existing validated and published submodels from STICS (Brisson et al., 2003) for water and nitrate balances in soils, AZOFERT (Machet et al., 2004, 2017) for N mineralisation of soils and crop residues, AZODYN (Jeuffroy and Recous, 1999) for crop N uptake, NOE (Hénault et al., 2005) for N_2 and nitrous oxide emissions and VOLT'AIR (Génermont and Cellier, 1997) for ammonia emissions.

Syst'N attempts to chart a middle course between complex simulation models such as STICS (Brisson et al., 1998), which simulate many processes but require many input data, and more simple indicators commonly used by agricultural practitioners (e.g. N balance, N-use efficiency) but which have relatively little ability to explain phenomena. Therefore, the equations added to Syst'N were selected to conform to the input data that are generally available to targeted end-users, hence keeping Syst'N user-friendly.

2.2. Experimental data

Most of the parameters initially used to calibrate the new legumes (lucerne, faba bean and soya bean) were derived from previously published studies. The data used to calibrate and evaluate Syst'N were collected in French field experiments, in contrasting pedoclimatic contexts and with different experimental treatments, such as various amounts of N fertilisation or irrigation applied (Table 1; see Table S1 for more details). The objective was to find data with the highest diversity in experimental treatments, including sowing date, amounts of N fertiliser and irrigation applied, as well as cutting dates for lucerne as a perennial crop. Ultimately, fertiliser applications could be tested only for pea, faba bean and lucerne. Site-year-management (SYM) units that covered a wide range of crop-management practices with high measurement frequency were chosen for the calibration dataset (6, 6, 9 and 17 for pea, faba bean, lucerne and soya bean, respectively), and the remaining SYM units formed the evaluation dataset (12, 3, 32 and 9 SYM, respectively).

2.3. Adaptation and calibration method

To begin adapting Syst'N, equations and corresponding parameters that represented plant processes (e.g. phenology, biomass accumulation, BNF) were chosen (Fig. 1). First, specific characteristics of each legume crop were identified. If the existing Syst'N equations could not simulate these characteristics or the resulting N dynamics satisfactorily, the equations were supplemented or modified based on those in existing models. Initial parameters for the crops were set based on a literature review of existing models and plant physiology articles, or directly on measurement datasets if parameter values were not found in the literature.

Table 1
Experimental data used to parameterise Syst’N.

Species	Dataset	Total site-year-management units with available measurements						References
		Total	Leaf area index	Aboveground biomass	Aboveground N content	N fixed	Soil N content	
Lucerne (<i>Medicago sativa</i> L.)	Calibration	9	9	9	9		3	Thiébeau et al. (2011) Justes et al., (2002, 2001);Lemaire et al. (1985); Thiébeau et al., (2011, 2004)
	Evaluation	32	13	30	30		22	
Pea (<i>Pisum sativum</i> L.)	Calibration	6	4	6	6	6	6	Guinet et al. (2018) Voisin et al. (2002); Corre-Hellou et al. (2009); Launay et al. (2009);Naudin (2009); Pelzer et al. (2016)
	Evaluation	12	8	12	9		12	
Faba bean (<i>Vicia faba</i> L.)	Calibration	6	4	6	6	6	6	Guinet et al. (2018) Schneider et al. (2019);Schneider et al. (2021)
	Evaluation	3		3	3			
Soya bean (<i>Glycine max</i> L.)	Calibration	17	12	16	16	16	4	Guinet et al. (2018) Schoving et al. (2022)
	Evaluation	9	0	9	9	0	0	

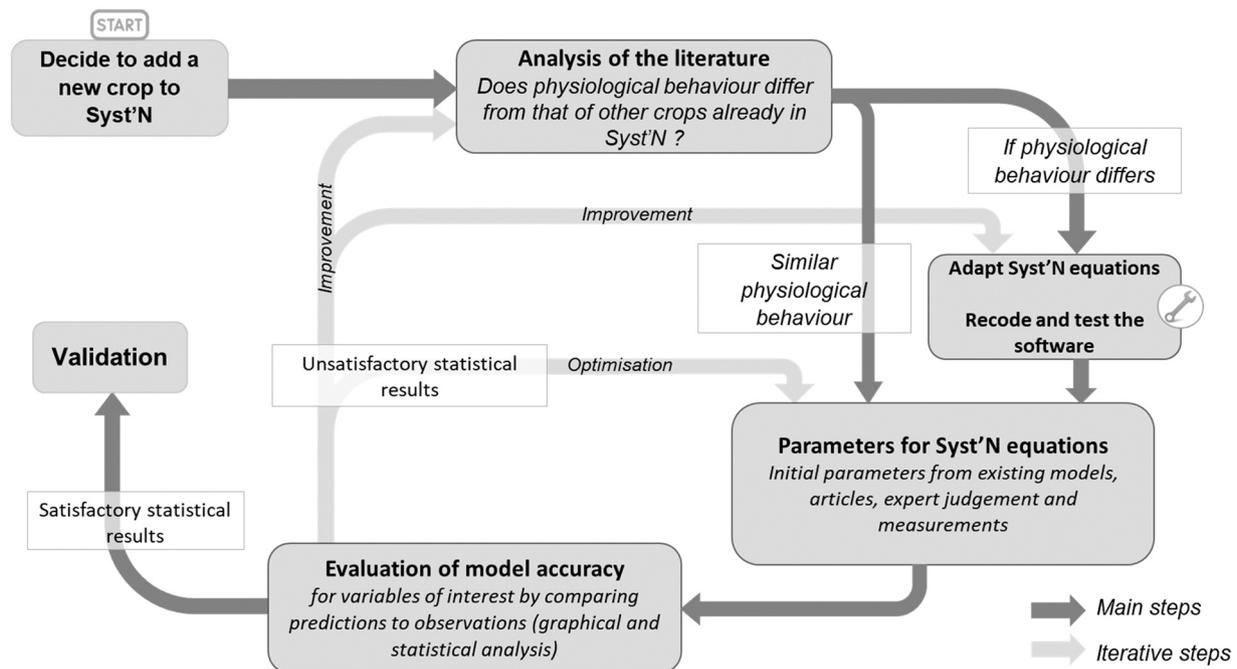


Fig. 1. Flowchart for adding a new crop to the Syst’N model.

We then graphically and statistically tested these initial equations and parameters using calibration datasets (Table 1). If predictions were unsatisfactory, some parameters were selected according to a set of criteria (e.g. sensitivity of variables of interest to the parameter, uncertainty) and tested for a range of values to improve prediction accuracy by optimising statistical indicators of accuracy.

2.4. Model assessment

As we were adding several legumes to Syst’N, we assessed it by considering important plant variables, such as aboveground biomass and N uptake, as well as BNF and soil mineral N content when datasets included them. Predicted target variables of Syst’N (i.e. N losses) were not evaluated because they were not measured in experiments and because only plant-related equations and parameters were modified in this study.

Model performance (with the optimised parameter set) was evaluated graphically as dynamics over the cropping cycle and plots of predictions vs. observations. It was quantified by calculating mean bias error (MBE) and its relative value (rMBE); root mean square error (RMSE) and its relative value (rRMSE); and model efficiency (EF) using data collected at harvest and throughout crop growth. These indicators are commonly

used to calibrate and evaluate agronomic models (Dumont et al., 2012).

$$MBE = \frac{1}{N} \sum_{i=1}^N (P_i - O_i) \quad (1)$$

$$rMBE = \frac{MBE}{\bar{O}} \times 100 \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (O_i - P_i)^2} \quad (3)$$

$$rRMSE = \frac{RMSE}{\bar{O}} \times 100 \quad (4)$$

$$EF = 1 - \frac{\sum_{i=1}^N (O_i - P_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} \quad (5)$$

where O_i and P_i are observed and simulated values for the i^{th} measurement, N is the number of these paired values and \bar{O} is the mean of observed values.

MBE and rMBE indicate whether a model underestimates (negative values) or overestimates (positive value) a given variable. Nevertheless, bias is not a sufficient measurement of the quality of a model: low bias can result from small prediction errors in all situations or instead from large prediction errors that compensate each other. Hence, the RMSE was also calculated (expressed in the same unit as the given variable) to identify this latter problem by squaring the difference between simulations and observations. Doing so, however, gives more weight to larger errors, which requires caution when interpreting RMSE, because a large RMSE can result from only one or two major differences. The rRMSE is more relevant for comparing variables with different units. Finally, EF assesses the overall performance of a model by comparing it to the mean of observations. EF ranges from $-\infty$ to 1, which facilitates interpretation: negative EF indicates that the model predicts no better than the mean of observations, whereas $EF = 1$ indicates a model with perfect accuracy. EF is relevant for comparing models or for comparing the same model's simulations of the same dataset using different sets of parameters/equations. Analysing these five statistical indicators from different groups of correlated indicators give a robust assessment of model prediction accuracy, as recommended by Yang et al. (2014). Like for Beaudoin et al. (2008) and Constantin et al. (2015a), (2015b), Syst'N predictions were considered satisfactory when EF exceeded 0.50 and rMBE was lower than 10% (Table 2). A 20% threshold was used for rRMSE, like for (Thiébeau, 2019a, 2019b), although a higher threshold (40%) was used to evaluate STICS predictions for lucerne (Strullu et al., 2020).

3. Results

3.1. Model description and parameterisation for legume crops

3.1.1. Mineralisation of crop residues

Syst'N already used a double exponential equation from the AZO-FERT tool to simulate net N mineralisation from crop residues (Machet et al., 2017):

$$N = N_{RO} \times (a_N - b_N e^{-kt} - c_N e^{-lt}) \quad (6)$$

where N is amount of N mineralised; N_{RO} is the initial amount of N in crop residues and a_N , b_N , c_N , l and k are coefficients that describe the mineralisation kinetics of N.

Before this study, the equation was parameterised for a variety of legume residues. The same parameterisation was used in this study. Inspired by the model TNT2 (Casal et al., 2019) for grazed or cut perennial crops (including lucerne in Syst'N), an additional N sequestration pool was added during crop development depending on grazing or cutting practices. After crop harvest or cover crop destruction, this pool of organic N mineralises.

3.1.2. Biological nitrogen fixation

As shown by the systematic literature review and quantitative statistical analysis of Anglade et al. (2015), legume species differ significantly in their median percentages of N derived from the atmosphere (% Ndfa), due mainly to the species' sensitivity to abiotic factors (e.g. soil mineral N content, soil water content, temperature) and to their

Table 2

Indicators used to assess model accuracy. MBE=relative mean bias error, rMBE=relative mean bias error, RMSE=root mean square error, rRMSE=relative root mean square error, EF=model efficiency.

Indicator	Range of values	Ideal value	Satisfactory range
EF	$[-\infty ; 1]$	1	> 0.5
MBE	$[-\infty ; +\infty]$	0	
rMBE	$[-\infty ; +\infty]$	0	$ rMBE < 10\%$
RMSE	$[0 ; +\infty]$	0	
rRMSE	$[0 ; +\infty]$	0	$< 20\%$

phenological characteristics (e.g. phenological stages, nodule establishment rate) (Guinet et al., 2018; Pampana et al., 2018). In the first version of Syst'N, the equation used to predict BNF was based on the AFISOL-Pea model (Vocanson, 2006) but it was adapted only for pea. In the present study, it was necessary to consider the diversity of BNF processes among legume species. The most common method for estimating %Ndfa of legume species in mechanistic crop models is to calculate a potential or maximum BNF rate which is then decreased by the influence of environmental factors: in their review, Liu et al. (2011) identified nine simulation models (Sinclair Model, EPIC, Hurley Pasture Model, Schwinning Model, CROPGRO, SOILN, APSIM, Soussana Model and STICS) that simulated legume BNF. Each model considered one or more of the following factors: soil temperature, soil-plant water, soil-plant N, plant carbon and phenological stage. Some BNF models are calibrated and parameterised for only one legume species, whereas others can simulate a wide range of legume species with different characteristics and geographic ranges.

To adapt Syst'N to a variety of legume species (grain and forage), we chose to add the BNF submodel of STICS (Brisson et al., 2009; Corre-Hellou et al., 2007), because it (i) is adapted to the French pedoclimatic context, (ii) is adapted for a wide range of legumes (e.g. field pea, soya bean, faba bean, lucerne) and (iii) considers all the environmental factors mentioned except carbon dynamics (ignored by Syst'N). The BNF equations of STICS were modified slightly to conform to the input data available in Syst'N (i.e. using air temperature instead of soil temperature for the temperature-weighting factor) and to the variables already calculated by Syst'N (beginning of nodulation associated with the beginning of BNF, nodule death associated with the final stage of seed abortion) (Fig. 2). The parameters specific to these equations, which also resulted from parameterisation of STICS, varied among species (Table 3).

3.1.3. Phenology

As for most crops, legume phenology is controlled mainly by air temperature and photoperiod. As a simple crop model, Syst'N calculates phenological stages using only sums of growing degree-days. According to their photo-thermal sensitivity, legumes can be classified into three main categories: photoperiod-insensitive, day-neutral and photoperiod-sensitive (short-day or long-day) (Roberts and Summerfield, 1987). As many studies observed, sensitivity to photoperiod is even more important for legume species, because it drives their transition to the reproductive stage (i.e. flowering) (Baranger et al., 2010; Confalone, 2008; Iannucci et al., 2008; Schneider and Huyghe, 2015). Because flowering stops (e.g. root growth), modifies (e.g. remobilising N, BNF) or triggers (e.g. plant senescence) some plant processes, and thus influences N dynamics, it seemed important for Syst'N to predict flowering time accurately. However, simulating photoperiod and its effects on crop phenology would (i) be too complex for such a DSS, (ii) require new input data (e.g. latitude) and (iii) require new parameters for the photoperiod sensitivity for each crop, which seems difficult to define. Thus, we chose to add the actual flowering date as optional input data. Indeed, a survey of Syst'N users indicated that they often observe it and thus could provide it as input data. When flowering date is provided, Syst'N calculates all phenological stages from it; if not, it calculates stages from the crop parameter that represents the number of degree days from sowing to flowering. When parametrising annual legumes, we decided to distinguish soya bean of types 00 and I, as their stages differ greatly.

3.1.4. Perennial legumes

We modified Syst'N greatly to capture specific characteristics of perennial crops, such as several cuts and regrowth sequences. In the first version of Syst'N, an equation from TNT2 (Casal et al., 2019) that estimated the change in plant biomass and N content when cutting grassland (Nitschelm et al., 2018) was used and adapted to represent other perennial crops such as lucerne. The residual aboveground

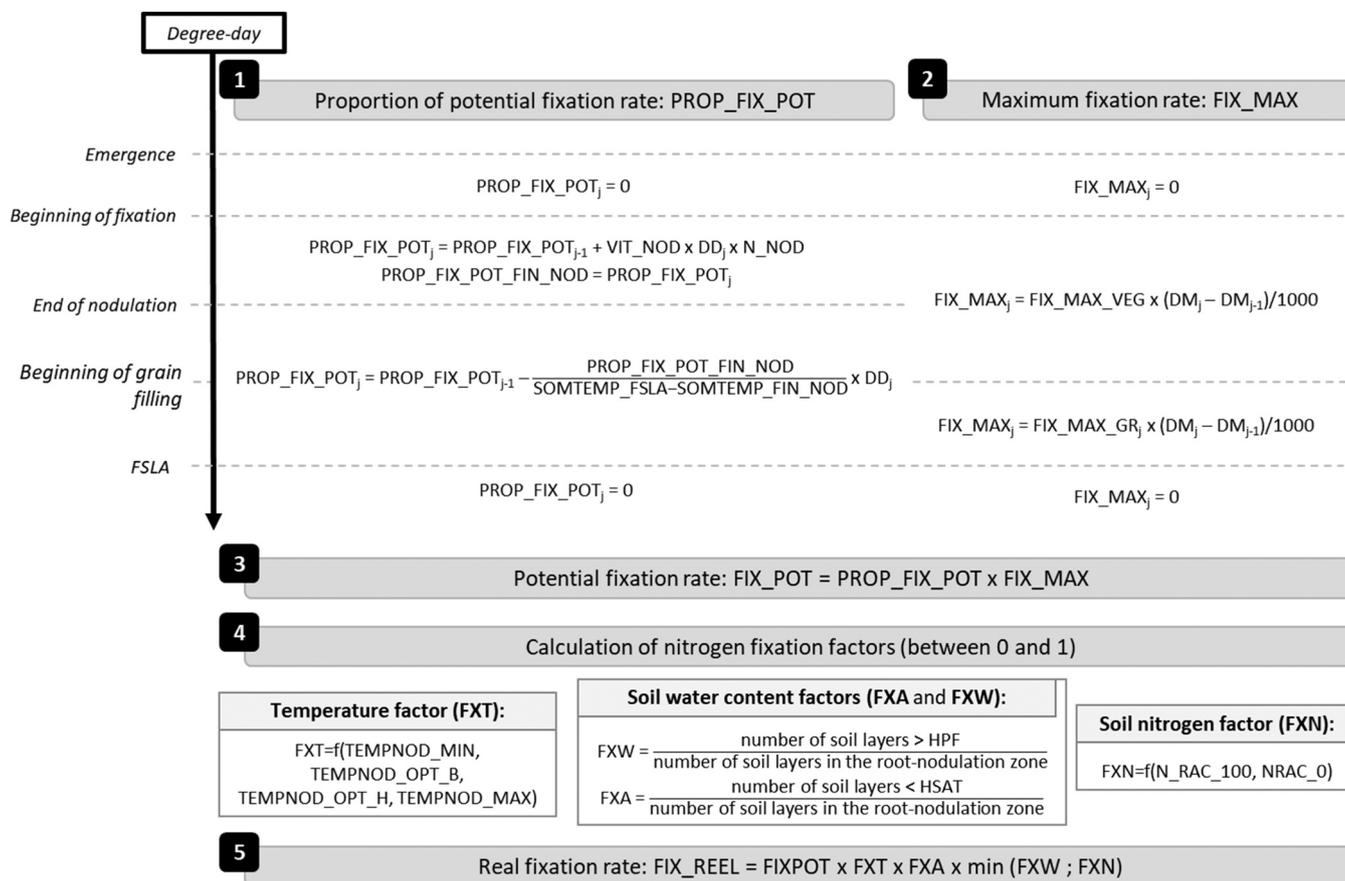


Fig. 2. Description of the biological nitrogen fixation (BNF) submodel added to Syst’N (adapted from the STICS model). See Table 3 for definitions of variables not defined in the figure. Numbers in black boxes indicate the order of the calculation steps.

biomass that remains in the field after a cut is calculated from the cutting height. Nevertheless, plant growth differs between seedlings and crop regrowth (after harvest or dormancy), as observed by Thiébeau et al. (2011) and Lemaire et al. (1985) for lucerne, due to crop defoliation and storage of reserves in roots, which supports regrowth after cutting or after winter. To keep Syst’N relatively simple, it contains two parameter sets to simulate seedlings and crop regrowth separately instead of using complex equations to represent reserve management by perennial crops, as in STICS versions for perennial crops (Strullu et al., 2014, 2020).

Some vigorous perennial legumes, such as lucerne, become dormant during winter (Undersander et al., 1997). Dormancy is triggered mainly in autumn by two factors: photoperiod and temperature (Maurières, 2003). As mentioned, simulating photoperiod would require new input data from users and make Syst’N more complex. An equation from CropSyst (Confalonieri and Bechini, 2013) was a good compromise to add dormancy to Syst’N in a relatively simple way (Fig. 3). This equation was adapted slightly in Syst’N to fit with its existing equations of biomass growth and N uptake. The parameters used in these equations were calculated from the optimisation measurement dataset. For simulated plant N content, this adaptation delays crop regrowth after winter and resets crop-stage variables, thus avoiding the unexpected early physiological maturity predicted without the dormancy equation (Fig. 4).

3.2. Results of model evaluation

3.2.1. The final parameters for legumes in Syst’N were set by the calibration method described (Table S2)

3.2.1.1. Calculating phenological stages from the actual flowering date. To

evaluate effects of calculating phenological stages from the observed flowering date on the accuracy of Syst’N predictions, the statistical indicators were calculated for predictions based on a dataset with or without the actual flowering date. The latter dataset was smaller than the measurement dataset, as it contained only the site-year-management (SYM) units in which flowering had been observed. The accuracy of predicted total aboveground plant N (Figs. 5C and 5D) content and BNF (Figs. 5E and 5F) increased, and that of predicted aboveground biomass remained good (Figs. 5A and 5B), which indicated the relevance of calculating phenological stages from the actual flowering date (as input data), as flowering is an important stage for BNF and N uptake. The rMBE were low (−6% to 19%) and showed Syst’N’s tendency to overestimate total aboveground plant N (rMBE = 19%, Fig. 5C) but underestimate BNF (rMBE = −6%, Fig. 5E). However, the relatively good EF (0.73–0.85) of predictions of all plant variables confirmed that Syst’N predicted growth and N assimilation (uptake plus BNF) throughout the crop cycle (from juvenile to mature stages) better when stages were calculated from the actual flowering date. All rRMSE were satisfactory (< 41%).

3.2.2. Accuracy of predictions over the crop cycle

3.2.2.1. Aboveground biomass. Predicted biomass agreed with observations throughout each legume crop’s growing season for both calibration and evaluation datasets ($\text{EF} > 0.75$, $9\% < \text{rMBE} < 13\%$), considering a dataset with or without flowering date (Figs. 6A and 6B). Positive rMBE showed Syst’N’s tendency to overestimate aboveground biomass, especially for lucerne with the calibration dataset (data not shown). Prediction error was high (rRMSE of 40% for both datasets) due to senescence defoliation and the loss of biomass related to respiration

Table 3
Parameters of the biological nitrogen fixation submodel added to Syst'N.

Parameter name (unit)	Description	Crop							
		Lucerne		Faba bean		Pea		Soya bean	
		Initial	Regrowth	Winter	Spring	Winter	Spring	Type I	Type 00
CONC_N_NOD_SEUIL (kg N.ha ⁻¹ .mm ⁻¹ water)	Maximum soil nitrogen concentration threshold for nodule establishment	1.6	1.6	4.5	4.5	2.0	2.0	2.14	2.5
VIT_NOD (nodules.degree-day ⁻¹)	Nodule establishment rate	0.0037	0.0015	0.0068	0.0068	1.0	1.0	0.003	0.003
FIX_MAX_VEG (kg N.t DM ⁻¹)	Maximum nitrogen fixation capacity per t of dry matter produced before the grain-filling stage (DRG)	-	-	32	40	28	30	-	-
FIX_MAX_GR (kg N.t DM ⁻¹)	Maximum nitrogen fixation capacity per t of dry matter produced after the grain-filling stage (DRG)	-	-	17	17	9.5	9.5	-	-
FIX_MAX_CONST (kg N.day ⁻¹)	Constant capacity for maximum nitrogen fixation by the crop	6.0	6.0	-	-	-	-	6.0	6.0
TEMP_NOD_MIN (°C)	Minimum cardinal temperature for nodule activity	0	0	0	0	0	0	0	0
TEMP_NOD_OPT_B (°C)	Low optimal cardinal temperature for nodule activity	15	15	12	12	10	10	20	20
TEMP_NOD_OPT_H (°C)	High optimal cardinal temperature for nodule activity	25	25	25	25	25	25	36	36
TEMP_NOD_MAX (°C)	Maximum cardinal temperature for nodule activity	35	35	40	40	35	35	50	50
N_RAC_100 (kg N.ha ⁻¹ .cm ⁻¹ soil)	Nitrogen concentration threshold for full activity of nodules	0.12	0.12	1.6604	1.6604	0.3612	0.3612	1.6604	1.6604
N_RAC_0 (kg N.ha ⁻¹ .cm ⁻¹ soil)	Nitrogen concentration threshold that inhibits nodule activity	0.82	0.82	9.4759	9.4759	1.2058	1.2058	4.4804	4.4804
PROF_NOD_MAX (cm)	Maximum nodulation depth	40	40	30	30	30	30	40	40
ECARTTEMP_FIN_NOD (degree days)	Degree-day difference between the phenological reference stage and end of nodulation (FIN_NOD)	-100	0	550	550	1200	1316	700	530
ECARTTEMP_FSLA (degree days)	Degree-day difference between the phenological reference stage and final stage of seed abortion (FSLA)	300	300	800	1000	1200	1316	1000	750
ECARTTEMP_DRG (degree days)	Degree-day difference between the phenological reference stage and beginning of grain-filling (DRG)	0	0	250	250	200	150	400	400
SOMTEMP_DEBUT_FIX (degree days)	Sum of degree days from sowing to the beginning of fixation	250	0	340	310	235	235	320	320

during dormancy (Justes et al., 2002), which Syst'N ignores for all crops. Hence, Syst'N assumes that aboveground biomass does not change during dormancy. Nevertheless, it can be considered a time-lag in growth dynamics that does not influence Syst'N prediction, as they became more accurate after dormancy (Fig. 7).

For each legume crop, all statistical indicators were good: rMBE was low (i.e. $-13\% < \text{rMBE} < 20\%$), EF was satisfactory (> 0.59) and rRMSE was rather satisfactory ($< 48\%$) (Table 4).

3.2.2.2. Plant nitrogen content

3.2.2.2.1. Total aboveground nitrogen content. Total aboveground N content was predicted accurately using both the calibration and evaluation datasets considering a dataset with or without flowering date for evaluation (Figs. 6C and 6D): rMBE was low (19% and 5%, respectively), EF was high (> 0.70) and rRMSE was satisfactory ($< 40\%$). Prediction of aboveground N content was satisfactory for faba bean and pea, with good rMBE ($< 16\%$), high EF (0.87) and low rRMSE ($< 25\%$) (Table 4). Despite lower EF (0.61) and higher rRMSE (44%), predictions for lucerne using the evaluation dataset remained satisfactory, with a slight overestimation of the dynamics. In contrast, rMBE (23%), EF (0.48) and rRMSE (44%) for soya bean showed a tendency for Syst'N to overestimate aboveground N content (Table 4).

3.2.2.2.2. Aboveground nitrogen fixation. The parameters related to BNF defined for each crop (Table 3) yielded good predictions (Fig. 6E and Fig. 6F), with a high EF (> 0.78) and low rMBE ($-13\% < \text{rMBE} < 6\%$) for pea, faba bean and soya bean (Table 4). Because observed data were not available for lucerne, we compared predictions to data from the literature (Kelner et al., 1997; Schneider and Huyghe, 2015; Wivstad et al., 1987; Xie et al., 2015). They showed highly variable %Ndfa of

20–90%, which seemed to be explained in part by variable amounts of mineral N in the soil. These percentages were found in the predictions, with a mean %Ndfa of 70% for unfertilised plots and 50% for plots that had received mineral N fertiliser. For the other legume crops, this good accuracy was verified throughout growing season (EF=0.80, low rMBE). EF remained high and bias remained low with the evaluation dataset, indicating that Syst'N was able to reproduce the wide range of cumulative BNF at harvest (33–265 kg N.ha⁻¹).

3.2.2.3. Soil water content and soil mineral nitrogen content. Syst'N predicted soil water content better during evaluation (EF = 0.44) than calibration (EF = -2.38), despite lower rMBE (-7% and 20% , respectively) and higher rRMSE (33% and 24%, respectively) (Fig. 8). Despite satisfactory indicators, we observed threshold effects. Syst'N had difficulty predicting the wide range of soil water content observed (2.5–33.2%), as it was constrained by threshold values of the pedo-transfer classes used to define field capacity (θ_{FC}) and wilting point (θ_{WP}) as a function of soil texture (9.1–26.4%).

Soil N content was predicted less well using the calibration and evaluation datasets, with negative EF (-0.19 and -0.24 , respectively) and high rRMSE (45% and 67%, respectively) (Fig. 8). The low EF (-0.76) and high rRMSE (69%) for lucerne (Table 4) could be explained mainly by temporal shifts (data not shown). First, nodule activation, which enables BNF, and moderate N uptake from the soil can occur sooner than predicted. This delay in prediction by a few days may cause Syst'N to underestimate soil N content at a given date significantly. Secondly, the simple equation used to simulate dormancy may delay N uptake during biomass regrowth and cause Syst'N to overestimate soil N content for a few weeks, which has little influence on predicted N losses.

Parameter name (unit)	Description	Crop
DORMANCE (Boolean)	Indicates whether the crop can become dormant	Lucerne
DEB_DORM (date)	Beginning of the potential dormancy period	15 Nov
FIN_DORM (date)	End of the potential dormancy period	10 Mar
T_DORMANCE (°C)	Temperature below which crop dormancy begins, or above which dormancy ends, if maintained as a mean daily temperature for 7 consecutive days during the dormancy period, or after the dormancy period, respectively	5

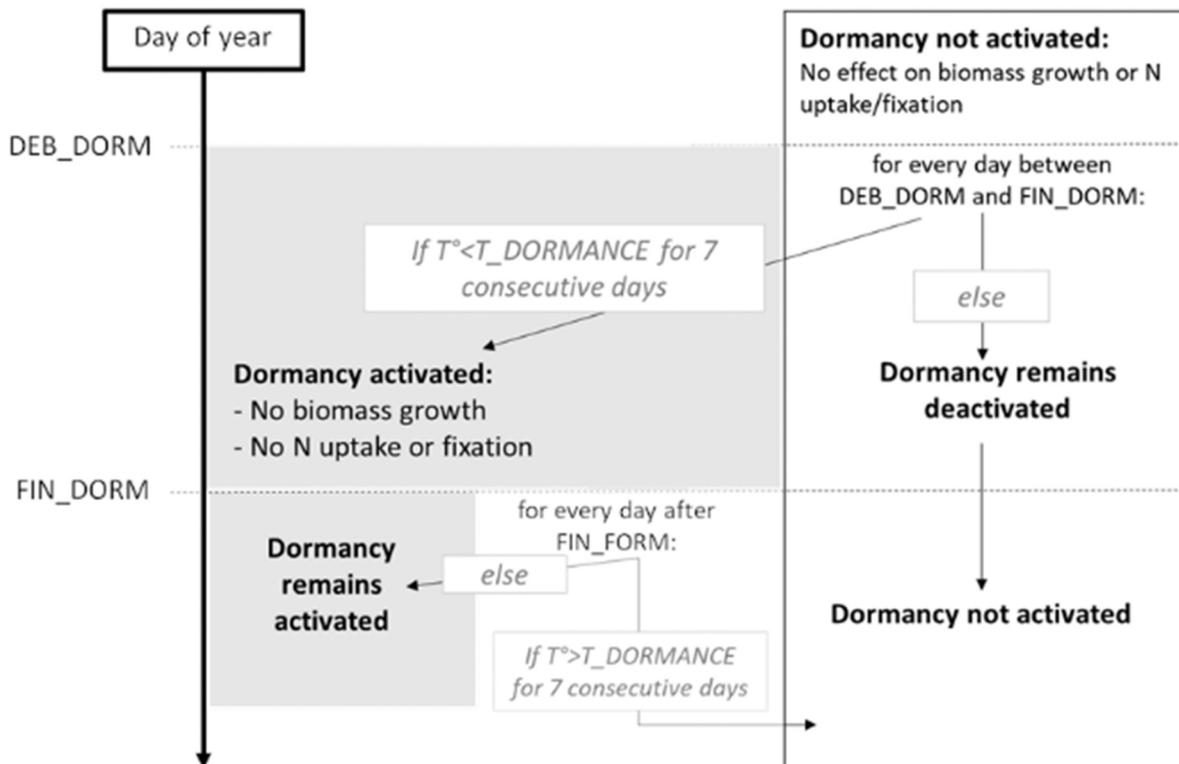


Fig. 3. Description of the dormancy submodel added to Syst’N (adapted from that in the CropSyst model).

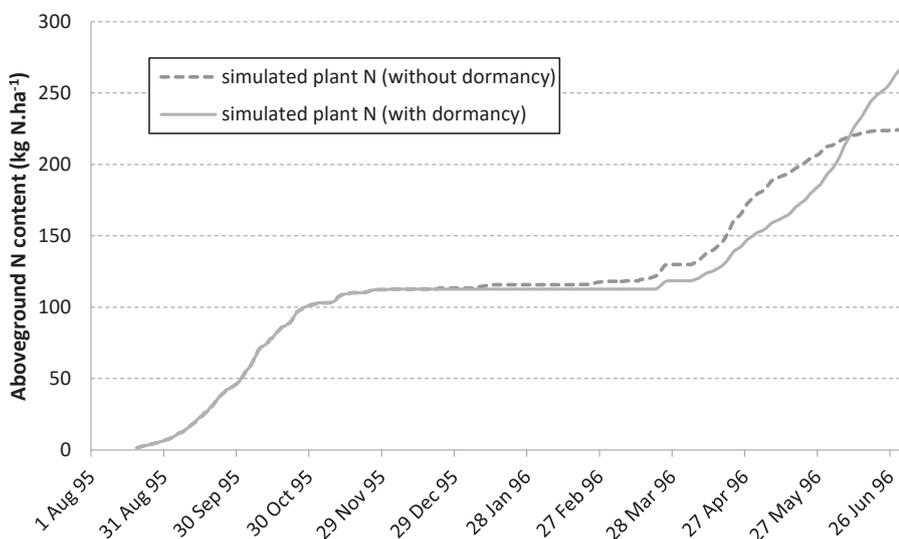


Fig. 4. Syst’N predictions of lucerne aboveground N content before and after adding equations to simulate dormancy.

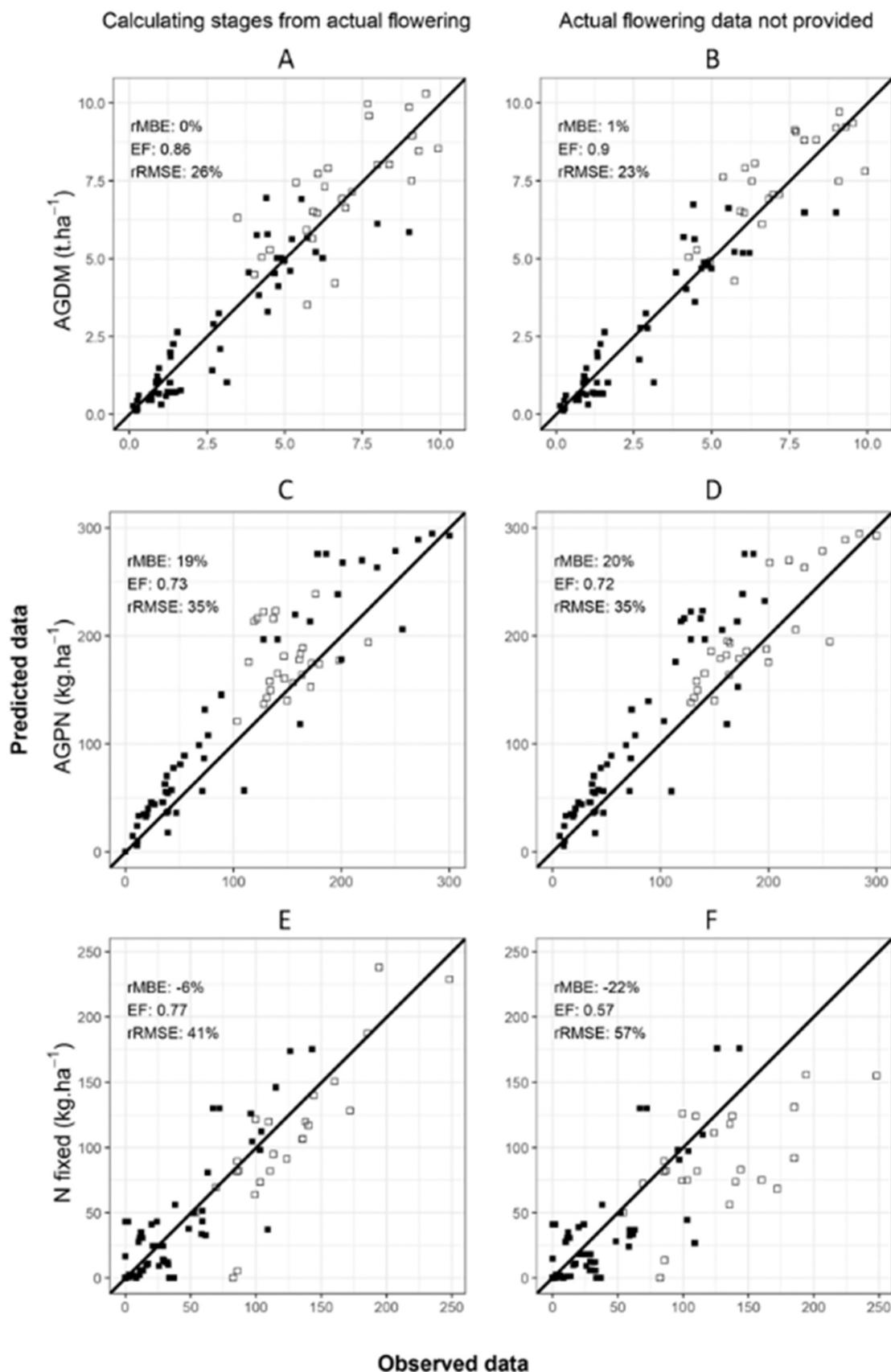


Fig. 5. Comparison of aboveground dry matter (AGDM), aboveground plant nitrogen content (AGPN) and biological N fixation observed vs. that predicted by Syst’N with the calibration dataset, with or without calculating phenological stages from the actual flowering date. rMBE=relative mean bias error, EF=model efficiency, rRMSE=relative root mean square error. The black line is the 1:1 line. White symbols correspond to the end of the growing season. Black symbols correspond to earlier stages.

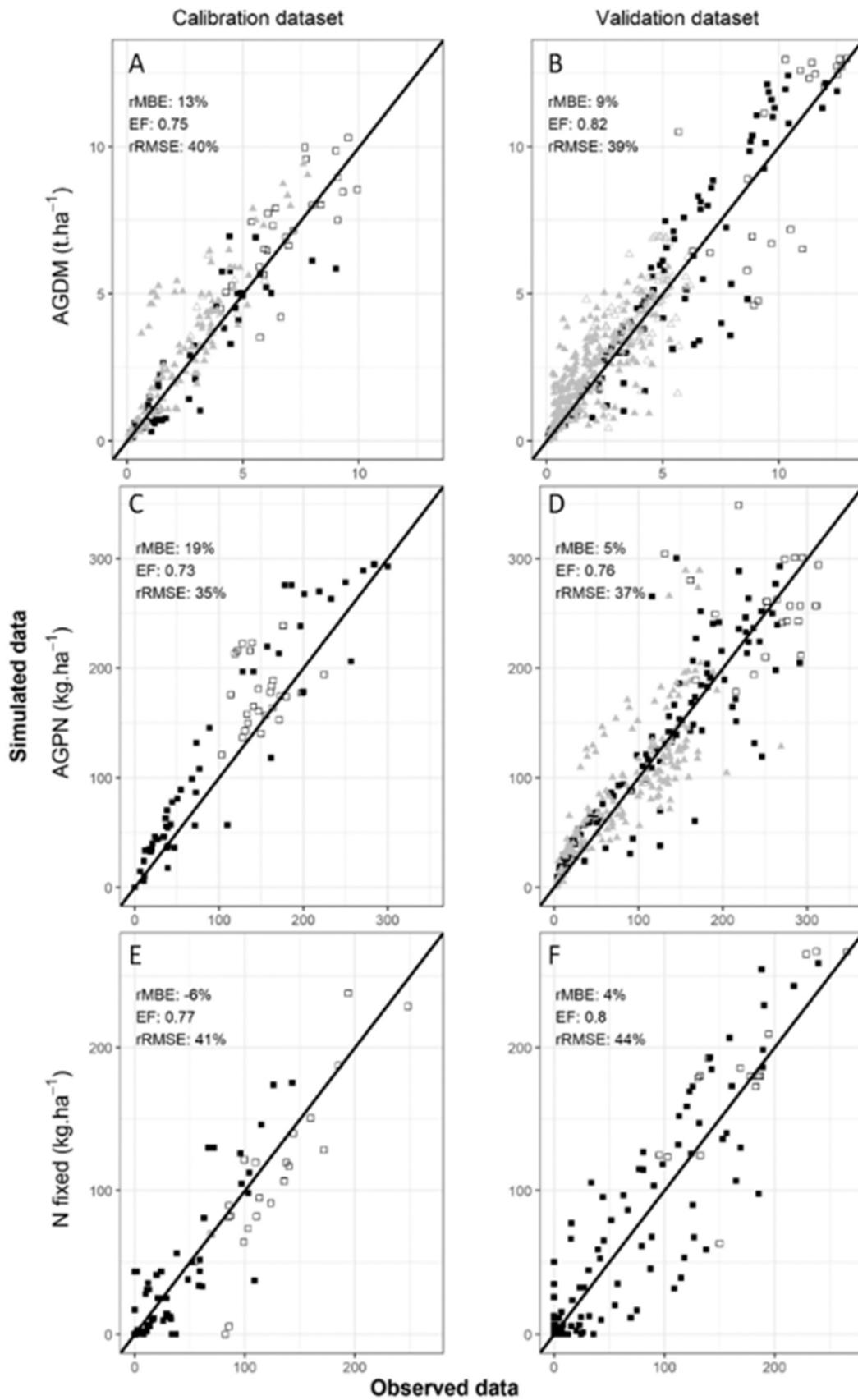


Fig. 6. Comparison of aboveground dry matter (AGDM), aboveground plant nitrogen content (AGPN) and biological N fixation observed vs. that predicted by Syst’N with the calibration and evaluation datasets. rMBE=relative mean bias error, EF=model efficiency, rRMSE=relative root mean square error. The black line is the 1:1 line. White symbols correspond to the end of the growing season. Black symbols correspond to earlier stages.

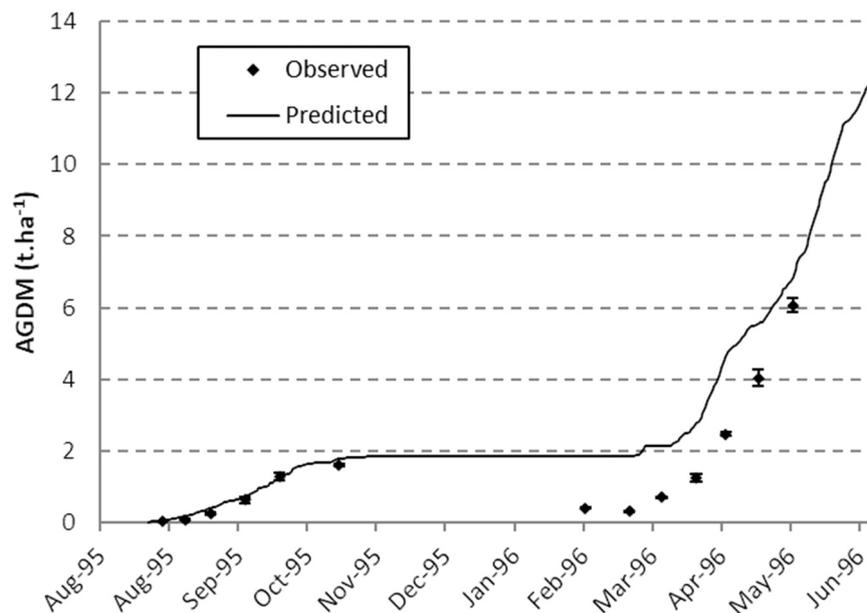


Fig. 7. Example of observed and predicted aboveground dry matter before and after dormancy using the evaluation dataset (site: Châlons-en-Champagne). Error bars indicate standard deviations.

Table 4

Statistical indicators of predictions of aboveground biomass, aboveground nitrogen (N) content and biological N fixation (BNF) for each legume crop with the evaluation dataset. EF=model efficiency, MBE=relative mean bias error, rMBE=relative mean bias error, RMSE=root mean square error, rRMSE=relative root mean square error.

Indicator	Prediction	Faba bean	Pea	Soya bean	Lucerne
EF	Biomass	0.82	0.90	0.71	0.59
	N content	0.87	0.87	0.48	0.61
	BNF	0.78	0.78	0.83	NA
	Soil water content	-28.71	0.44	-3.72	No data
	Soil N content	-0.2	0.49	-2.97	-0.76
MBE	Biomass	0.70	0.24	-0.65	0.43
	N content	16.21	0.08	31.52	5.63
	BNF	-9.24	-0.25	4.03	NA
	Soil water content	5.55	-0.75	5.21	No data
	Soil N content	-9.09	-5.93	-0.49	4.1
rMBE	Biomass	20%	5%	-13%	19%
	N content	16%	0%	23%	7%
	BNF	-13%	0%	6%	NA
	Soil water content	22%	-4%	22%	No data
	Soil N content	-14%	-11%	-1%	6%
RMSE	Biomass	0.94	1.28	1.59	1.08
	N content	20.45	32.99	59.83	36.19
	BNF	20.64	32.54	26.55	NA
	Soil water content	7.21	6.35	6.33	No data
	Soil N content	26.35	26.53	16.19	43.79
rRMSE	Biomass	27%	27%	33%	48%
	N content	20%	25%	44%	44%
	BNF	30%	45%	38%	NA
	Soil water content	29%	32%	27%	No data
	Soil N content	42%	50%	41%	69%

3.2.3. Nitrogen effect of legumes on subsequent crops

Dynamics of N mineralisation after a legume crop were evaluated only for lucerne because of the specific calculations in Syst'N for grazed or cut perennial crops. For the other crops, the N effect of legumes is calculated directly with the AZOFERT equation, which has already been evaluated (Machet et al., 2017).

Predicted N mineralisation in the soil after lucerne was compared to measurements from Justes et al. (2001). In this experiment, mineralisation from humus and from residues returned to the soil after lucerne destruction were differentiated. Dynamics of simulated N mineralisation

from lucerne residues and soil organic matter accurately reproduced observations for two years in two situations: lucerne cut just before destruction (3% error between prediction (331 kg N ha⁻¹) and observation (340 kg N ha⁻¹) after two years) and lucerne cut one week before destruction (8% error between prediction (368 kg N ha⁻¹) and observation (400 kg N ha⁻¹) after two years). Thus, with less than 10% error, predictions of N mineralisation were satisfactory and confirmed Syst'N's ability to represent long-term effects of lucerne residues.

4. Discussion

4.1. A generic and user-friendly crop model able to simulate a diversity of legumes

This study showed that the generic equations of Syst'N can simulate a variety of legumes species: those with cool-season adaptation (pea and faba bean), warm-season adaptation (soya bean) and a perennial cycle (lucerne). The accuracy of predicted aboveground biomass and N assimilation (uptake plus BNF) was satisfactory for all 4 legume species, with rMBE less than 10% (2–9%) and EF greater than 0.50 (0.74–0.81), which are consistent with the guidelines of Beaudoin et al. (2008) and Constantin et al. (2015a), (2015b). Moreover, the accuracy of these predictions are similar to those for other species parameterised in Syst'N (unpublished).

Prediction of BNF was improved by adding the actual flowering date as input data. Users in the field can obtain the actual flowering date easily, which allows Syst'N to remain adapted to its purpose and user-friendly. In addition, the flowering date can also be estimated using a simple phenology algorithm (Schoving et al., 2020) and then used as an input variable for Syst'N.

4.2. Water balance prediction

Syst'N's ability to simulate soil water and mineral N contents, both of which are used to calculate N leaching, is less satisfactory than that for biological variables, as all statistical indicators except rMBE lay above satisfactory thresholds. Our predictions of soil N content were similar to those of STICS with faba bean (Falconnier et al., 2019), whose rMBE, EF and rRMSE were -10%, -1.42% and 51%, respectively, using an evaluation dataset.

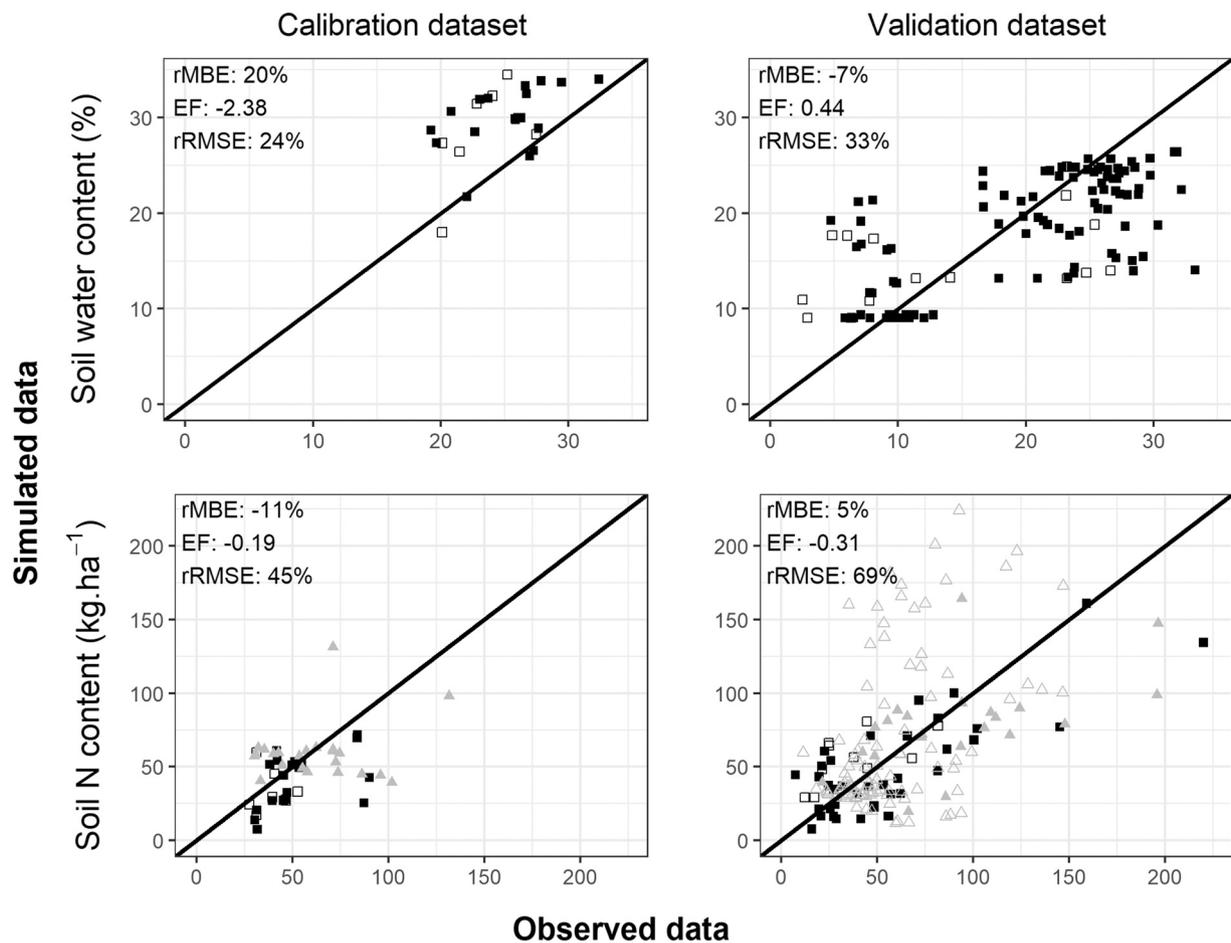


Fig. 8. Comparison of soil water content and soil nitrogen content observed and that predicted by Syst'N using calibration and evaluation datasets. rMBE=relative mean bias error, EF=model efficiency, rRMSE=relative root mean square error. The black line is the 1:1 line. White symbols correspond to the end of growing season. Black symbols correspond to earlier stages.

Syst'N predicted both low and high observed soil water contents poorly (Fig. 8) due to the pedotransfer classes it uses to estimate θ_{FC} and θ_{WP} as a function of percentages of clay, silt and sand. Indeed, large differences in soil texture can yield the same characteristic water contents, as observed for 9 site-year-management (SYM) in this study (Fig. 8). For example, because silty-clay loam (30% clay, 62% silt, 8% sand) and sandy-clay loam (14% clay, 32% silt, 54% sand) are considered to be the same in Syst'N's pedotransfer classes, both have θ_{FC} of 32.3% and θ_{WP} of 14.0%. Many studies have related soil texture to water-retention characteristics of the soil (Gupta and Larson, 1979) using pedotransfer classes or functions. Classes were used in the first version of Syst'N instead of functions based on the results of Al Majou et al. (2007), who showed that "simple" texture-based pedotransfer classes allowed water-retention characteristics to be predicted as accurately as with more sophisticated pedotransfer classes or functions. However, using pedotransfer classes inevitably leads to threshold effects, which decreases the accuracy of predictions of water balance and thus nitrate leaching. Tóth et al. (2015) developed new hydraulic pedotransfer functions valid for the pedoclimatic context in France. The most accurate predictions were obtained using the clay percentage, silt percentage, bulk density, organic carbon and pH as parameters, all of which are available as input data in Syst'N. In future versions, using pedotransfer functions could improve predictions of soil water content, in particular by overcoming the threshold effect caused by pedotransfer classes. Soil water content has a strong influence on BNF and soil N content, but also on water transfer and thus on N leaching, which is one of the main outputs of the model. In addition, the parameters θ_{FC} and

θ_{WP} could be used as input data if they are available. Nevertheless, we have noted that the end-users of Syst'N do not often know the values of these parameters.

4.3. Specifying a large number of plant parameters

Using the actual flowering date to calculate phenological stages and the new BNF equation required adding 2 and 16 new plant parameters, respectively, specific to legume species. Thus, 77 agro-physiological parameters for each species must now be defined to simulate a new legume crop in Syst'N. Although some of these parameters require good knowledge of the agro-physiological behaviour of the crop, particularly for N processes (e.g. parameters of N-dilution curves), many of them can be approximated easily using knowledge of other crops already parameterised in Syst'N. Moreover, despite the large number of plant parameters, Syst'N is easier to adapt than most other models, such as STICS, which requires specifying over 200 crop- and cultivar-specific parameters; however, it was developed by researchers to investigate a wider diversity of cropping systems and consider many more processes (Brisson et al., 2009).

4.4. Strong simplification of biological processes for perennial legumes

Predictions highlight high overestimation of aboveground biomass and N content immediately after dormancy due to the lack of equations to simulate senescence and mobilisation of reserves in Syst'N. However, this trend is relatively brief: along with rapid biomass regrowth in the

spring, reserves stored in roots during autumn and winter are remobilised to shoots (Justes et al., 2002). The accuracy of predicted aboveground biomass and N content increased after a few weeks and became satisfactory during the cuts in spring. This simplification in Syst'N delays N uptake from the soil in the spring but has little influence on soil N content during winter, a key variable used to predict nitrate leaching. As shown by Strullu et al. (2014) for *Miscanthus* × *giganteus*, total aboveground N content decreases only slightly in winter despite a strong decrease in aboveground biomass. Rapid remobilisation of N temporarily stored in perennial organs has also been observed for other legumes, such as white clover (*Trifolium repens* L.) (Robin et al., 1999), which supports this hypothesis. In the future, the simple equation that maintains aboveground biomass and N content constant during winter could be applied to other perennial crops in Syst'N.

As mentioned, Syst'N has two parameter sets to simulate seedlings and crop regrowth separately, instead of using a complex model to represent reserve management by perennial crops, as in STICS versions for perennial crops. These STICS versions, initially developed for *Miscanthus* reserves (Strullu et al., 2014) and then for lucerne (Strullu et al., 2020), consider the N fluxes between perennial organs (e.g. the taproot) and non-perennial organs (i.e. leaves, stems and roots) as a function of abiotic stress, photoperiod and phenological stages using a single set of parameters, but they required defining more compartments in the model and are thus complex. STICS version for lucerne resulted in EF values of 0.70 for aboveground biomass and 0.60 for N content, while Syst'N using less complex equations gave similar EF (0.60 for both biomass and N content). However STICS predictions were slightly more accurate (rRMSE of 31% vs 36% for Syst'N). So, despite being less accurate, the predictions of Syst'N were reasonable for perennial crops given it uses simpler equations than STICS.

Comparing Syst'N's lucerne predictions to those of CropSyst highlights the difficulty in applying a model to contrasting environments using a single set of crop parameters. Using CropSyst, Confalonieri and Bechini (2013) obtained an rRMSE of 3–6% for predictions of total aboveground biomass after calibrating crop parameters that partly considered local conditions, especially for dormancy and development temperature. We used a submodel of CropSyst for dormancy in Syst'N, but due to the small amount of measurement data over the period, Syst'N's parameters were not calibrated to local conditions of the datasets, which may explain the lower rRMSE for Syst'N. Moreover, lucerne parameters were calibrated based on a variety grown in northern France, and the influence of decreasing photoperiod varies among lucerne varieties. Syst'N represents the effect of photoperiod on crops indirectly using two fixed calendar dates that can stop growth during a period with a short photoperiod. Unfortunately, this study could not test the ability of Syst'N and this parameter set to simulate southern varieties of lucerne, which may start growing earlier in the spring.

5. Conclusion

Legumes can play a key role by providing N to cropping systems and thus enhancing the N self-sufficiency of farms (Cellier et al., 2016; Vertès et al., 2010, 2015). Therefore, farmers and their advisers increasingly attempt to insert legume species into their crop sequences; besides the effects on their crop production that they can observe, they need results for and knowledge about N fluxes that they cannot assess themselves, such as N supply to subsequent crops and emissions to the environment. Adapting Syst'N to several legumes with different crop cycles and BNF capacities but keeping it relatively simple was both a challenge and an expected development, given its utility to non-researcher users.

We chose and combined equations from research crop models such as STICS and CropSyst to maintain the simplicity of Syst'N for end users. Although some BNF equations required many parameters, users need to supply only one additional parameter (flowering date) if they want to predict BNF. Based on the literature, experiments and optimisation, we developed a set of parameters that provided satisfactory predictions of

legume aboveground biomass and N content. In contrast, Syst'N predicted soil N content less well, mainly due to temporal shifts. Nevertheless, they remain relevant and are an important prerequisite for simulating N emissions that are of particular interest to users. The next step will be to improve predictions of soil N and water content, to evaluate the accuracy of Syst'N predictions of N emissions (i.e. nitrate leaching, nitrous oxide emissions) and to do so at the scale of a cropping sequence that includes legumes.

CRedit authorship contribution statement

V. Parnaudeau: Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Bedu M., Lefèvre L.:** Conceptualization, Methodology, Formal analysis, Investigation, Validation, Writing – review & editing. **Dupont A., Dubrulle P.:** Software. **Reau R.:** Conceptualization, Funding acquisition. **Debaeke P., Guinet M. Thiébeau P.:** Resources, Writing – review & editing. **Jeuffroy M.-H., Voisin A.-S.:** Conceptualization, Resources. **Maury P., Schneider A., Schoving C.:** Resources.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Philippe Debaeke (co-author) in editorial board of EJA.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.126999.

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